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QFT nonlinearities in vacuum and plasmas.

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QFT nonlinearities in vacuum and plasmas

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Overview

- Why are we interested in the low energy quantum vacuum and high field physics?
- Plasmas and the quantum vacuum topically connected.
- How can we probe the vacuum?
- Quantum effects in plasmas.
- Examples.
- What might the future bring?
Developments


- Current divide: relativistic optics & nonlinear QED. (Mourou et al., RMP, 2006; Marklund & Shukla, RMP, 2006; Salamin et al. Phys. Rep., 2006)

- New developments in numerical and experimental tools. (e.g. Fonseca, Proc. HPCPAST 2002; Trines et al., PRL, 2005)

- Near future importance: laboratory astrophysics, e.g. hydro, nuclear astro. (Remington et el., RMP, 2006)

- Questions in fundamental physics:
  - ... etc.
Soluble models

Exact solutions:

*In eighteen-century Newtonian mechanics, the three-body problem was insoluble. With the birth of general relativity around 1910 and quantum electrodynamics in 1930, the two- and one-body problems became insoluble. And within modern quantum field theory, the problem of zero bodies (vacuum) is insoluble.*

R.D. Mattuck

→ We need methods, experimental and theoretical, to deal with such issues.
The quantum vacuum

- Quantum electrodynamics: fundamental theory of photon-matter interactions.

- 1930’s: Weisskopf, Heisenberg, Euler etc. + Dirac discovers nonlinear quantum vacuum.

- 1950’s: Schwinger shows vacuum polarization from QED.

- Special relativity + Heisenberg’s uncertainty principle → vacuum acts as virtual pair plasma [e.g. RMP, 2006].

- Quantum vacuum: from NEMS to QG.
Signs of QFT vacuum on photons

a) Nonlinear electrodynamics.
   • QED vacuum polarization (Schwinger field).
   • String theory Born–Infeld electrodynamics (string tension) (Tseytlin, hep-th/9908105).
   • Minicharge particles?

b) Phase- and polarization effects.
   • Axion-like particles.

c) Vacuum dispersion
   • Derivative QED corrections.
   • Spacetime coarsening:
     - Loop QG.
     - Non-commutative ST.
     - Double special relativity.
   Nonlinearities + dispersion?
   Hawking effect, BH entropy.
Nonlinear vacuum effects

Delbrück scattering

Casimir effect

Photon splitting

Elastic photon scattering
High field generation

- Many high phenomena directly tractable with next generation laser systems.
- Some phenomena require intensities above current experimental limits.

Opportunity to reach the Schwinger field
\[ \sim 10^{29} \text{ W/cm}^2 \]
Probing new regimes

Accelerators vs. laser systems:
Probing new regimes

▷ New possibilities to probe low-energy domains.

▷ In particular, light pseudo-scalar particles (e.g. PVLAS, Fermi Lab, DESY...).


▷ Is it possible to probe Lorentz invariance properties (dispersion)?

▷ Parametrized theory to restrain models.
Why?

Astrophysics

Giga-gauss field in laser-plasmas.

A touch of gravity

Thermodynamics

Quantum fields

Spacetime structure

Modify the Standard Model?

\[ g \phi \mathbf{E} \cdot \mathbf{B} \Rightarrow \]

New physics

High precision intense optical experiments

Example: photon–photon scattering

\[ \sigma_{\gamma\gamma} \approx 0.7 \times 10^{-29} \left( \frac{\hbar \omega}{1 \text{ MeV}} \right)^6 \text{cm}^2 \]

\[ \mathcal{L} = \mathcal{L}_0 + \frac{\varepsilon_0 \alpha}{90\pi E_{\text{crit}}^2} \left[ \left( E^2 - c^2 B^2 \right)^2 + 7c^2 (E \cdot B)^2 \right] \]

\[ E_{\text{crit}} = m_e^2 c^3 / e \hbar \sim 10^{16} \text{ V/cm} \]

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Example: photon–photon scattering

- Why? (See also Tommasini’s talk!)
  - “Clean” vacuum experiment.
  - Benchmark for experimental development.
  - Could new physics be probed?
  - Constraining nonlinear electrodynamics:

$\mathcal{L}_{BI} = \kappa^2 \left[ 1 - \sqrt{1 + \frac{\kappa^{-2}}{2}(E^2 - B^2)} - \frac{\kappa^{-4}}{16}(E \cdot B)^2 \right]$  

- Derivative corrections to HE lagrangian

$\mathcal{L}_D = \sigma \varepsilon_0 \left[ (\partial_a F^{ab})(\partial_c F_{cb}) - F_{ab} \Box F^{ab} \right]$  

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Contains string tension

Prop. to Compton wavelength^2
Pair production

\[ \hbar \omega_\gamma \gtrsim 2m_e c^2 \]
\[
\begin{align*}
\gamma + \gamma & \rightarrow e^- + e^+ \\
\gamma + B_0 & \rightarrow e^- + e^+ + B_0
\end{align*}
\]

- Positronium interaction with laser: Small scale muon pair collider! (Müller et al. PRD 74, 074017 (2006)).
- Laser-pair plasma interactions give new experimental possibilities.

Burke et al., PRL 79, 1626 (1997)
Pair production

- "Schwinger mechanism" for fields with spatial and temporal variation.
- Temporal compression: increased production rate.
- Spatial compression: lower production rate.
- Laser fields production rate unknown.
- Schwinger limit: more than necessary?
- Need for theory (e.g. world-line instantons, e.g. Gies, Dunne).
- Will experiment come first? Non-perturbative aspect of QED.
Harmonic generation

Vacuum harmonics possible in principle (Di Piazza et al., PRD 72, 085001 (2005); Fedotov & Narozhny, PLA 362, 1 (2007)).

Nonperturbative surprises?
Plasmas in QED vacuum

- Combined effect of ultrarelativistic magnetized plasmas and QED \( \rightarrow \) new electromagnetic modes. Example:

\[
n^2 = \frac{4\alpha}{45\pi} \left[ \left( \frac{E}{E_{\text{crit}}} \right)^2 n^2 + \left( \frac{B_0}{E_{\text{crit}}} \right)^2 \right] n^2 \pm \frac{\hbar}{m_e} \frac{\omega_p^2}{\omega} \frac{E_{\text{crit}}}{E}
\]

- New dispersive properties in strong field environments, e.g. pulsar magnetospheres.

- Plasma breaks Lorentz invariance.

- Possible boost for certain plasma parameters (Di Piazza et al.)?
Nonlinear plasma-QED photon splitting.

Linear decay channel: pair plasma suppression in pulsar magnetospheres (Shabad & Usov, Nature (1982))

PRL 98, 125001 (2007)
Colliding photons

Two colliding light pulses. Criteria for vacuum collapse:

\[ \left( \frac{\alpha}{90\pi} \right)^{1/2} \frac{|E|}{E_{\text{crit}}} > \frac{r_p}{\lambda_p} \]

Supplemented by

\[ \frac{W_p}{\lambda_p r_p^2} > \frac{90\pi}{\alpha} \varepsilon_0 E_{\text{crit}}^2 \]

Sufficiently long pulses for collapse to occur. See also Kharzeev & Tuchin, PRA, 2007. Or pair production before Schwinger limit?
Vacuum dynamics

- Dynamics similar to laser-plasmas
- Catastrophic collapse governed by NLSE and acoustic wave equation
- Evolution determined by the system

\[ i \partial_t E + \frac{1}{2} v'_g \nabla^2 \nabla_\perp E + \mu \mathcal{E} E = 0 \]

\[ (\partial_t^2 - \frac{1}{3} c^2 \nabla^2) \mathcal{E} = \nu \nabla^2 |E|^2 \]

(PRL 91, 163601 (2003))
Vacuum dynamics

**Pulse, \( t=0 (\text{sec})^{-1} \)**

**Radiation, \( t=0 (\text{sec})^{-1} \)**

**Energy density, \( k_{ct}=100 \)**

**Energy density, \( k_{ct}=300 \)**

**Energy density, \( k_{ct}=350 \)**

**Energy density, \( k_{ct}=400 \)**
Gigagauss laboratory fields

- Currently, gigagauss laboratory fields generated in solid-laser interactions.
- Magnetization of the vacuum for future lasers?
- Principle: magnetic field exerts Lorentz force on vacuum fluctuations.
- Possible to use for QED experiments, or to muddled?
Hawking–Unruh effect

> Testing the Hawking–Unruh effect (Chen & Tajima, PRL, 1999; Schützhold et al., PRL, 2006, 2008; Brodin et al., CQG, 2008); electron acceleration.

\[ k_B T_H = \frac{\hbar g}{2\pi c} \]
\[ k_B T_U = \frac{\hbar a}{2\pi c} \]
Unruh effect

> Need electrons plasma to get measurable signal.

> Problem: hole in Larmor radiation pattern decreases like $1/N$ for $N$-electron plasma.

> Use spectral pattern; detectable soft x-ray signal from Unruh effect?

> Achievable by present day high-intensity lasers.

> Connection: dynamical Casimir?
Quantum aspects of spacetime

- Non-commutative spacetime

\[ [x^{\mu}, x^{\nu}] = i\theta^{\mu\nu} \]

QFT on NCST interpreted as low-energy limit of open strings or limit on length scales. IR/UV mixing: high-energy affects low-energy.

- Canonical quantum gravity and loop quantum gravity: spacetime quantization, coarsening.

- String theory: low-energy case gives birefringence-free nonlinear electrodynamics.

http://www.cpt.univ-mrs.fr/~rovelli/
Quantum aspects of spacetime

  - Birefringence.
  - Anisotropic speed of light.
  - Anisotropy in quantum fields.
  - Violations of universality of free fall and the universality of the gravitational redshift.
  - Time and space variations of “constants”.
  - Charge non-conservations.
  - Anomalous dispersion.
  - Decoherence and spacetime fluctuations.
  - Modified interference.
  - Non-localities.
Dispersion: invariant scale length (such as Planck scale) introduces Lorentz invariance violations (massive and massless).


\[ c^2 k^2 = \omega^2 \left( 1 \pm \xi \frac{\hbar \omega}{E_{QG}} \right), \quad E_{QG} \sim 10^{19} \text{ GeV} \]

From NCST and LQG. Test through γ-ray bursts.

Possibility for coherent states: “nonlocality” and bulk property (Magueijo, PRD, 2006; Hossenfelder, PRD, 2007)

\[ \xi = \xi(|A|) \sim \xi_0 |A|^a \]
Conclusions

➢ Laser science is entering a new era:
  ➢ Relativistic optics.
  ➢ Nonlinear quantum vacuum.

➢ Possible to experimentally probe uncharted QED sectors.

➢ Atomic systems in ultra-intense fields.

➢ Laser probes of elastic photon-photon scattering.

➢ “Clean” experiment, benchmark experiment?

➢ Interesting future possibilities:
  ➢ Collective quantum vacuum effects.
  ➢ Higher harmonic generation.
  ➢ Unruh test, dynamical Casimir effect, accelerated mirrors?.